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State Engg. Exams

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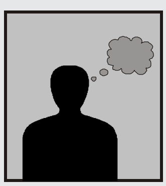


Detailed Explanations of Try Yourself *Questions*

Mechanical Engineering

Thermodynamics

MADE EASY PUBLICATIONS

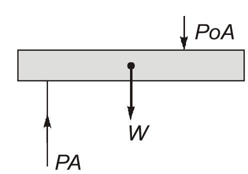
1 Basic Concepts and Zeroth Law of Thermodynamics

Detailed Explanation of Try Yourself Questions

T1 : Solution

Energy supplied to motor $= \dfrac{0.50 \times 0.746}{0.65} = 0.574$ kJ/sec. [HP = 0.746 kW]

T2 : Solution



FBD of piston

At the instant, when piston just begins to move;

$$P_0A + W = P_2A$$

$$\Rightarrow \quad P_2 = P_0 + \frac{W}{A}$$

$$P_2 = 100 + \frac{50 \times 9.81 \times 4}{\pi \times 0.1^2 \times 10^3}$$

$$P_2 = 162.45 \text{ kPa}$$

$$\frac{T_2}{P_2} = \frac{T_1}{P_1} \qquad (\because V_1 = V_2)$$

$$\frac{T_2}{162.45} = \frac{300 + 273}{250}$$

$$\Rightarrow \quad T_2 = 372.34 \text{ K or } 99.34°\text{C}$$

T3 : Solution (b)

The properties of the system which are independent of mass under consideration are called intensive properties.

Examples: Pressure, Temperature, Density and all specific properties.

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2 Energy Interactions (Heat & Work)

Detailed Explanation *of* Try Yourself Questions

T1 : Solution

$$U = 34 + 3.15\,PV$$
$$P_1 = 170 \text{ kPa},\ V_1 = 0.03 \text{ m}^3$$
$$P_2 = 400 \text{ kPa},\ V_2 = 0.06 \text{ m}^3$$

Change in internal energy of the fluid during the process,

$$\begin{aligned} U_2 - U_1 &= 34 + 3.15\,P_2 V_2 - 34 - 3.15\,P_1 V_1 \\ &= 3.15\,(P_2 V_2 - P_1 V_1) \\ &= 3.15\,(400 \times 0.06 - 170 \times 0.03) \\ &= 59.535 \text{ kJ} \end{aligned}$$

Now $\qquad P = aV + b$

or $\qquad 170 = a \times 0.03 + b \qquad \ldots \text{(i)}$

and $\qquad 400 = a \times 0.06 + b \qquad \ldots \text{(ii)}$

Eq. (ii) — Eq. (i), we get

$$400 - 170 = a\,(0.06 - 0.03)$$

or $\qquad a = 7666.67 \text{ kN/m}^3$

Submitting the value of a in Eq. (i), we get

$$170 = 7666.67 \times 0.03 + b$$

or $\qquad b = -60 \text{ kN/m}^2$

Work trasnfer in involved during the process,

$$\begin{aligned} W_{1\text{-}2} &= \int_1^2 PdV = \int_1^2 (aV + b)dV = b(V_2 - V_1) + a\frac{(V_2^2 - V_1^2)}{2} \\ &= -1.8 + 10.35 = 8.55 \text{ kJ} \end{aligned}$$

From first law of thermodynamics,

$$\begin{aligned} Q_{1\text{-}2} &= (U_2 - U_1) + W_{1\text{-}2} \\ &= 59.535 + 8.55 = 68.085 \text{ kJ} \end{aligned}$$

T2 : Solution (408.92)

Given: Initial pressure, P_1 = 110 kPa, Initial volume, V_1 = 5 m^3, Final volume, V_2 = 2.5 m^3, Polytropic index, n = 1.2

For polytropic process,

$$P_1 V_1^n = P_2 V_2^n$$

$$\Rightarrow \quad 110 \times (5)^{1.2} = P_2 \times (2.5)^{1.2}$$

$$\Rightarrow \quad P_2 = 252.7136 \text{ kPa}$$

$$\text{Work done, } \delta W = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{110 \times 5 - 252.7136 \times 2.5}{1.2 - 1}$$

$$= -408.92 \text{ kJ}$$

So, Absolute volume of work done = 408.92 kJ.

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3 First Law of Thermodynamics

Detailed Explanation of Try Yourself Questions

T1 : Solution

Given: $M = 1$ kg, $P_1 = 1$ bar, $T_1 = 300$ K, $C_P = 750$ J/kgK, $W = 225$ kJ

From 1st law, we have

$$đQ = dU + đW$$

For insulated and rigid vessel,

$$đQ = 0,\ PdV = 0$$

$$\therefore \quad 0 = mC_V(T_2 - T_1) - 225$$

$$\therefore \quad 1 \times 750 \times (T_2 - 300) = 225$$

$$T_2 = 300 + \frac{225 \times 10^3}{750} = 600\text{ K}$$

From ideal gas relation, $V = C$

$$\therefore \quad \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

or,

$$P_2 = \frac{P_1}{T_1} \times T_2$$

$$P_2 = \frac{1 \times 600}{300} = 2\text{ bar}$$

T2 : Solution

Given: $V = 8\text{ m}^3$, $m_1 = 0$ (Initially evacuated), $P_i = 600$ kPa, $T_i = 306$ K, $P_2 = P_i = 600$ kPa, $Q = 1000$ kJ, $c_p = 1.005$ kJ/kgK, $c_v = 0.718$ kJ/kgK

For unsteady state, energy equation,

$$m_2u_2 - m_1u_1 = \dot{m}_ih_i - Q$$

$$\because \quad m_1 = 0,\ Q = 1000\text{ kJ}$$

From mass conservation, $m_i = m_2 - m_1$

$$\therefore \quad m_2u_2 = m_2h_i - Q$$

$$\text{or} \quad m_2(c_pT_i - c_vT_2) = Q$$

$$\frac{P_2V}{RT_2}\left(c_pT_i - c_vT_2\right) = Q$$

$$\text{or,} \quad \frac{600\times 8}{0.287}\left(\frac{1.005\times 306}{T_2} - 0.718\times 1\right) = 1000$$

$$\text{or,} \quad \frac{307.53}{T_2} - 0.718 = \frac{1000\times 0.287}{600\times 8}$$

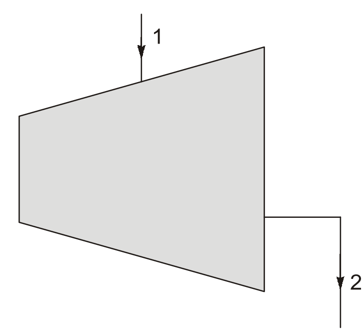
$$\frac{307.53}{T_2} = 0.777$$

$$\therefore \quad T_2 = 395.38 \text{ K}$$

T3 : Solution

Given: $\dot{m}_s = 500$ kg/s , $h_1 = 3500$ kJ/kg, $S_1 = 6.5$ kJ/kgK, $T_o = 500$ K, $h_2 = 2500$ kJ/kg, $S_2 = 6.3$ kJ/kgK

From entropy balance, we have,



$$S_1 + S_{gen} = S_2 + \frac{Q}{T_o}$$

For reversible process, $S_{gen} = 0$

$$\therefore \quad 6.5 = 6.5 + \frac{Q}{500}$$

$$\therefore \quad Q = 100 \text{ kJ/kg}$$

Now, from energy balance, $W = \dot{m}_s\left[(h_1 - h_2) + 100\right]$

$$= 500[(3500 - 2500) + 100]$$

$$W = 550 \text{ MW}$$

T4 : Solution

Work input is minimum for isothermal compression since area under P-V plot is minimum

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4 Second Law of Thermodynamics

Detailed Explanation of Try Yourself Questions

T1 : Solution

Energy collected, $E = 0.05 \text{ kW/m}^2$

$$\eta = 0.2$$

$$W = 1 \text{ kW}$$

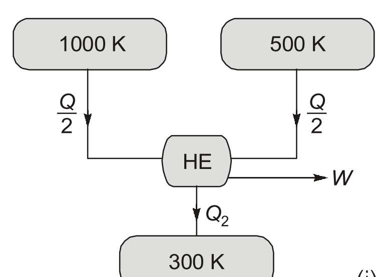
$$\eta = \frac{W}{Q}$$

$$0.2 = \frac{1}{Q}$$

or $$Q = \frac{1}{0.2} = 5 \text{ kW}$$

Minimum collected area, $$A = \frac{Q}{E} = \frac{5}{0.5} = 10 \text{ m}^2$$

T2 : Solution



(i)

For maximum thermal efficiency,

$$\Rightarrow \quad \oint \frac{Q}{T} = 0$$

$$\Rightarrow \quad +\frac{Q}{2000} + \frac{Q}{1000} - \frac{Q_2}{300} = 0$$

$$\Rightarrow \quad Q_2 = \frac{9}{20}Q$$

Using 1st law of thermodynamics

$$Q = Q_2 + W = \frac{9}{20}Q + W$$

$$W = \frac{11}{20}Q$$

$$\Rightarrow \quad \eta = \frac{W}{Q} = \frac{11}{20} = 55\%$$

T3 : Solution (b)

Clausius inequality is $\oint \frac{\delta Q}{T} \le 0$

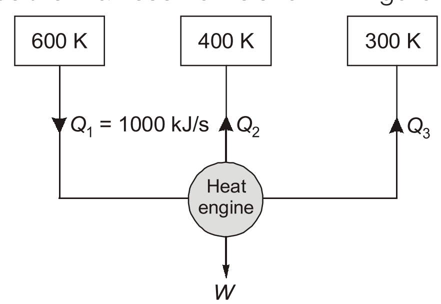
For reversible cycle, $\oint \frac{\delta Q}{T} = 0$

For irreversible cycle, $\oint \frac{\delta Q}{T} < 0$

So, this inequality is valid for any cycle.

T4 : Solution

A schematic diagram of a reversible heat engine operating with three thermal reservoir is shown in figure.



$$Q_1 = Q_2 + Q_3 + W$$

(As per 1st law of thermodynamics)

$$1000 = Q_2 + Q_3 + 50$$

$$\Rightarrow \quad Q_2 + Q_3 = 950 \text{ kJ/s} \quad \ldots(i)$$

$$\sum \frac{Q}{T} = 0$$

[Claussius inequality]

$$\Rightarrow \quad \frac{1000}{600} - \frac{Q_2}{400} - \frac{Q_3}{300} = 0$$

$$\Rightarrow \quad 3Q_2 + 4Q_3 = 2000 \quad \ldots(ii)$$

Solving equation (*i*) and (*ii*) we get

$$Q_2 = 1800$$

$$Q_3 = -850$$

⇒ Engine rejects 1800 kJ/s to the reservoir at 400 K and absorbs 850 kJ/s from the reservoir at 300 K.

So, net energy absorbed = 1000 + 850 = 1850 kJ/s

Thermal efficiency of the engine

$$\eta = \frac{\text{Net work done}}{\text{Heat absorbed}} = \frac{50}{1850} = 2.7\%$$

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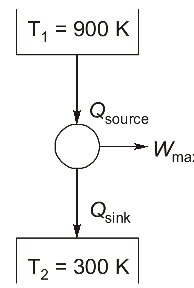
5 Entropy, Availability and Irreversibility

Detailed Explanation of Try Yourself Questions

T1 : Solution



Given: $T_1 = 900$ K

$T_2 = 300$ K

$m = 50$ kg

Final temperature of tank for maximum power production,

$$T_f = \sqrt{T_1 T_2} = \sqrt{900 \times 300} = 519.6\text{K}$$

$$W_{max} = Q_{source} - Q_{sink}$$

$$= mc_v (T_1 - T_f) - mc_v (T_f - T_2)$$

$$= mc_v [T_1 + T_2 - 2T_f]$$

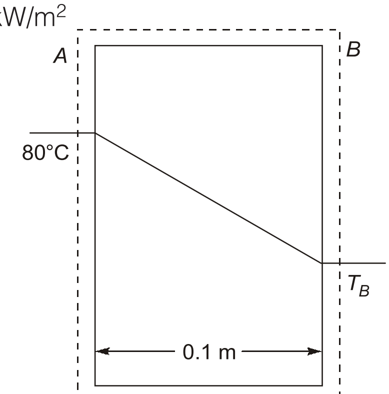
$$= 50 \times 0.718 [900 + 300 - 2 \times 519.6]$$

$$= 5772.72 \text{ kJ}$$

T2 : Solution

Given: Thermal conductivity of slab, K = 15 W/mK, Heat flux, Q = 4.5 kW/m^2

According to Fourier's law,



$$Q = -kA\frac{dT}{dx}$$

$$4500 = -15 \times \frac{(T_B - 80)}{0.1}$$

$$\Rightarrow \quad T_B = 50°\text{C}$$

$$\left(\frac{dS}{dt}\right)_{cv} = \dot{S}_i + \dot{S}_{gen} - \dot{S}_e$$

At steady state, $\left(\frac{dS}{dt}\right) = 0$

So, $$\dot{S}_{gen} = \frac{Q}{T_B} - \frac{Q}{T_A} = \frac{4500}{323} - \frac{4500}{353} = 1.18 \text{ W/m}^2\text{K}$$

T3 : Solution

It is the case of work potential of a fixed mass which is non-flow energy by definition.

Given: $T_1 = 300$ K

$P_1 = 1000$ kPa

$T_0 = 300$ K

$P_2 = 100$ kPa

$$\text{Mass of air in the tank, } m_1 = \frac{P_1V_1}{RT_1} = \frac{1000 \times 250}{0.287 \times 300} = 2903.6 \text{ kg}$$

Exergy content of compressed air per kg = $\phi_1 - \phi_2$

$$\phi_1 - \phi_2 = (u_1 - u_2) + P_0(v_1 - v_2) - T_0(s_1 - s_2)$$

$$= P_0(v_1 - v_0) - T_0(s_1 - s_0) \qquad [\because (u_1 - u_2) = 0, (s_2 = s_0), (v_2 = v_0)]$$

$$= P_0\left[\frac{RT_1}{P_1} - \frac{RT_0}{P_0}\right] - T_0\left[c_p l n\frac{T_1}{T_0} - R l n\frac{P_1}{P_0}\right]$$

$$= RT_0\left[\frac{P_0}{P_1} - 1\right] + RT_0 l n\frac{P_1}{P_0} = RT_0\left[\frac{P_0}{P_1} - 1 + l n\frac{P_1}{P_0}\right] \qquad [\because T_1 = T_0]$$

$$= 0.287 \times 300\left[\frac{100}{1000} - 1 + l n\frac{1000}{100}\right] = 120.76 \text{ kJ/kg}$$

Total exergy content of air, $X = m\phi$

$= 2903.6 \times 120.76$

$= 350646.22$ kJ = 350.6 MJ

Alternate:

$P_1V_1 = P_2V_2$ $[T = C]$

$\Rightarrow$ $1000 \times 250 = 100\ V_2$

$\Rightarrow$ $V_2 = 2500\ \text{m}^3$

Availability = Total work capability – Work done on atmospheric air

$$= P_1V_1 \ln\frac{V_2}{V_1} - P_{atm}(V_2 - V_1)$$

$= 250 \ln 10 - 0.1(2500 - 250)$

$= 350.646$ MJ

T4 : Solution

Given: $\Delta Q = 0$

$h_1 = 4142$ kJ/kg $\qquad h_2 = 2500$ kJ/kg

$\phi_1 = 1700$ kJ/kg $\qquad \phi_2 = 140$ kJ/kg

$T_0 = 300$ K

$\Delta KE = 0$ $\qquad \Delta PE = 0$

- Actual work/ kg of steam,

$$Q - W = m(\Delta h + \Delta PE + \Delta KE)$$

$$W_{act} = -\Delta h = -(h_2 - h_1) = (h_1 - h_2)$$
$$= 4142 - 2500 = 1642 \text{ kJ/kg}$$

- Maximum possible work/kg of steam

$$W_{rev} = (\phi_1 - \phi_2)$$
$$= 1850 - 140 = 1710 \text{ kJ}$$

- $$T_0 S_{gen} = W_{rev} - W_{act}$$

$\Rightarrow$ $$S_{gen} = \frac{W_{rev} - W_{act}}{T_0} = \frac{1710 - 1642}{300} = 0.23 \text{ kJ/kgK}$$

Alternate Solution:

Availability function for flow process = ϕ

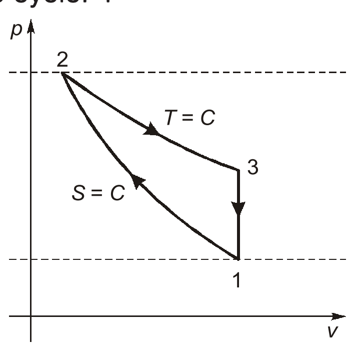
$$\phi = h - T_o s + \frac{C^2}{2} + gz$$

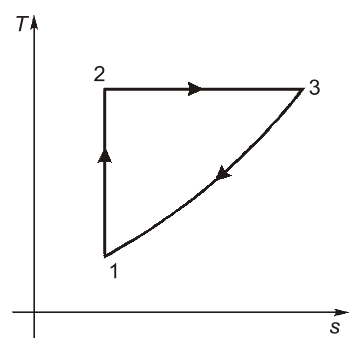
Neglecting ΔKE and ΔPE

$$\phi_1 - \phi_2 = (h_1 - h_2) - T_o (s_1 - s_2)$$
$\Rightarrow$ $$1850 - 140 = (4142 - 2500) - 300 (s_1 - s_2)$$
$\Rightarrow$ $$s_2 - s_1 = 0.23 \text{ kJ/kgK}$$

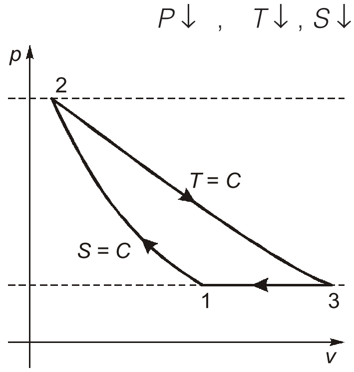
T5 : Solution

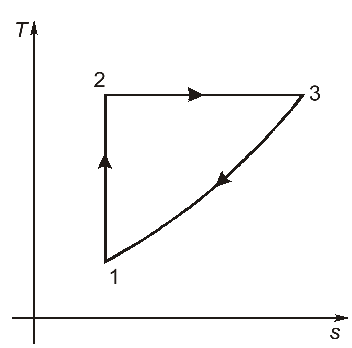
Number of the cycle: 4





1-2 $S = C$, $dQ = 0$
$dW < 0$
$\Rightarrow$ $dU > 0, T\uparrow$
2-3 $T = C$, $V\uparrow$, $S\uparrow$
3-1 $V = C$, $P\downarrow$, $T\downarrow, S\downarrow$





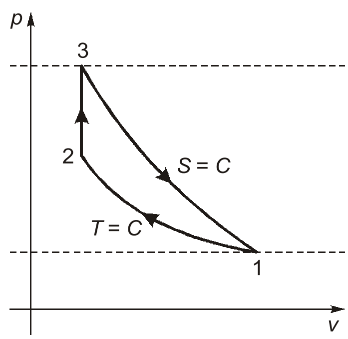
Process: 1-2 $S = C, dQ = 0$

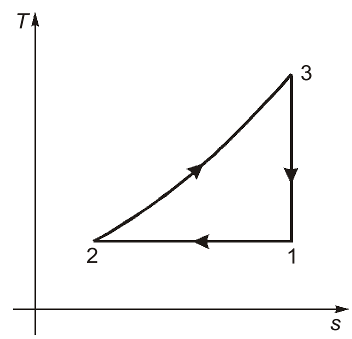
$$dW < 0$$

$\Rightarrow$ $$dU > 0,\ T\uparrow$$

Process: 2-3 $$T = C,\ V\uparrow,\ S\uparrow$$

Process: 3-1 $$P = C,\ V\downarrow,\ T\downarrow,\ S\downarrow$$





Process: 1-2 $$T = C,\ V\downarrow,\ S\downarrow$$

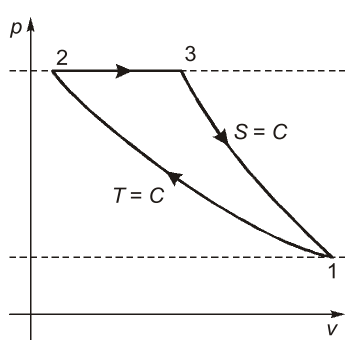
Process: 2-3 $$V = C,\ P\uparrow,\ T\uparrow,\ S\uparrow$$

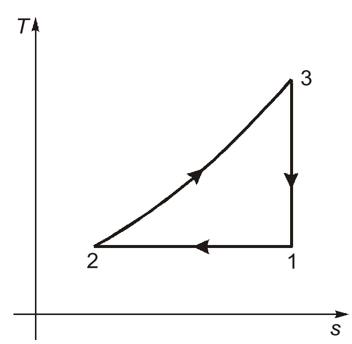
Process: 3-1 $$S = C,\ dW > 0$$

$$dU + dW = 0$$

$\Rightarrow$ $$dU = -\,dW$$

$$dU < 0 \Rightarrow T\downarrow$$





Process: 1-2 $$T = C,\ V\downarrow,\ S\downarrow$$

Process: 2-3 $$P = C,\ V\uparrow,\ T\uparrow,\ S\uparrow$$

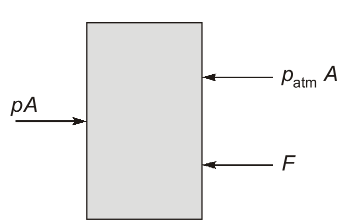
Process: 3-1 $$S = C,\ dW > 0$$

$\because$ $$dQ = 0$$

$\Rightarrow$ $$dU < 0 \Rightarrow T\downarrow$$

T6 : Solution

The initial and final pressure of the air are calculated from a free-body diagram of the piston, as follows



$$pA = p_{atm}A + F$$

$$pA = p_{atm} A + kx$$

$$pA = p_{atm} A + \frac{k(V_2 - V_1)}{A}$$

or
$$p = p_{atm} + \frac{k(V_2 - V_1)}{A^2}$$

Initially, spring force,
$$F = 0$$

∴
$$p_1 = p_{atm} = 100 \text{ kPa}$$

Final pressure,
$$p_2 = p_{atm} + \frac{k(V_2 - V_1)}{A^2} = 100 + \frac{10 \times (0.003 - 0.002)}{(0.02)^2}$$

$$= 100 + 25 = 125 \text{ kPa}$$

$$s_2 - s_1 = c_v \log_e \frac{p_2}{p_1} + c_p \log_e \frac{V_2}{V_1}$$

$$= 0.718 \log_e \frac{125}{100} + 1.005 \log_e \frac{0.003}{0.002}$$

$$= 0.16017 + 0.40749$$

$$= 0.56766 \text{ kJ/kgK}$$

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6 Properties of Pure Substance

Detailed Explanation of Try Yourself Questions

T1 : Solution

$v = 0.05$ m^3, $T_{sat} = 200°C = 273 + 200$ K $= 473$ K, $v_f = 0.001157$ m^3/kg, $v_g = 0.12736$ m^3/kg, $m_l = 8$ kg,
$v = v_f + xv_{fg}$

$$\frac{V}{(m_v + m_l)} = v_f + \frac{m_v}{m_v + m_l} v_{fg}$$

$$\frac{V}{\frac{m_v}{m_l} + 1} = m_l \cdot v_f + \frac{1}{\frac{1}{m_v} + \frac{1}{m_l}} \cdot v_{fg}$$

$$\frac{0.05 \times 8}{m_v + 8} = 8 \times 0.001157 + \frac{1}{\frac{1}{m_v} + \frac{1}{8}} \cdot (0.12736 - 0.001157)$$

$$m_v = 0.32 \text{ kg}$$

$$x = \frac{m_v}{m_v + m_l} = \frac{0.32}{0.32 + 8} = 0.03846$$

Now, Entropy, $s = s_f + xs_{fg}$
$= 2.3309 + 0.03846 \times 4.1014$
$= 2.4886$ kJ/kgK

T2 : Solution

Given: Specific weight of gas, $w = 16$ N/m^3

$$\text{Density of gas} = \frac{w}{g} = \frac{16}{9.81} = 1.63 \text{ kg/m}^3$$

Pressure of gas $= 0.25 \times 10^6$ N/m^2

Applying ideal gas equaton, $P = \rho RT$

$0.25 \times 10^6 = 1.63 \times R \times (273 + 25)$

$\Rightarrow$ $R = 514.68$ Nm/kgK

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7 Thermodynamic Relations and Clapeyron Equation

Detailed Explanation of Try Yourself Questions

T1 : Solution

$$\left(\frac{dP}{dT}\right)_s = 0.189 \text{ kPa/K}$$

Now using Clausius Clapeyron equation,

$$\left(\frac{dP}{dT}\right)_s = \frac{h_{fg}}{T_{sat} v_{fg}} = \frac{h_{fg}}{T_{sat}(v_g - v_f)}$$

$$v_g >> v_f$$

$$\left(\frac{dP}{dT}\right)_s = \frac{h_{fg}}{T_{sat} \cdot v_g}$$

$$0.189 \times 10^3 = \frac{h_{fg}}{298 \times 43.38}$$

$$h_{fg} = 2443.248 \text{ kJ/kg}$$

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